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ACID DEPOSITION STRATEGIES, THE LIMB PROGRAM AND IMPLICATIONS FOR CONTROL TECHNOLOGY REQUIREMENTS

by

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16. ABSTRACT The paper summarizes the various acid deposition bills introduced in the U.S. Congress during the past 2 years and discusses emission sources. A rapidly emerging technology called Limestone Injection/Multistage Burners (LIMB), which has the potential for simultaneous SO2 and NOx control, is described including background, current status, and plans. Finally, the possible implications of legislative alternatives and their effect on control technology requirements are presented. Acid rain continues to be a major environmental issue, and the importance of various acid precursor sources is still under debate. More than 15 bills that were pending in Congress required large sources of SO2 and/or NOx (two major pollutants resulting from the combustion of fuels) to reduce their emissions. Coal-fired utility boilers account for about 70% of the SO2 and 20-25% of the NOx emissions in the U.S. With this scenario, the timeliness and importance of low-cost control options applicable to these sources are evident. The breadth and depth of the research and development activities underway, both foreign and domestic, testify to the widespread interest in the potential benefits of these control technologies and the optimistic expectations for success in the on-going programs.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B 07B
Sulfur Dioxide	Stationary Sources	04B
Rain	Acid Rain	07D
Nitrogen Oxides	Limestone Injection/ Multistage Burners	21D
Acidity		08G
Coal		07A
Limestone		
Desulfurization		

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ACID DEPOSITION STRATEGIES, THE LIMB PROGRAM AND IMPLICATIONS FOR CONTROL TECHNOLOGY REQUIREMENTS

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INTRODUCTION

Acid rain continues to be a major environmental issue, and the importance of various acid precursor sources is still under debate. There were over 15 bills pending in the United States Congress that would require large sources of sulfur dioxide (SO_2) and/or nitrogen oxides (NO_x) to reduce their emissions. These are two major pollutants resulting from the combustion of fuels. Coal-fired utility boilers account for about 70% of the SO_2 and 20-25% of the NO_x emissions in the United States. With this scenario, the timeliness and importance of low-cost control options applicable to these sources are evident. The breadth and depth of the research and development activities underway, both foreign and domestic, testify to the widespread interest in the potential benefits of these control technologies and the optimistic expectations for success in the on-going programs.

This paper will summarize the various acid deposition bills introduced during the past 2 years and discuss emission sources. A rapidly emerging technology called Limestone Injection/Multistage Burners (LIMB), which has the potential for simultaneous SO_2 and NO_x control, will be described including background, current status, and plans. Finally, the possible implications of legislative alternatives and their effect on control technology requirements will be presented.

LEGISLATION -- THE IMPETUS FOR LOW-COST SO_2 AND SO_2/NO_x CONTROLS

The various acid deposition bills that were introduced into the 98th Congress during these past 2 years include approximately 15 bills which require emission reductions plus legislation that would: 1) accelerate R&D; 2) provide grants to states with acidified lakes for mitigating the damage (whatever the source of the damage); 3) improve our data base on the rate of atmospheric transport, transformation reactions, and deposition of both dry and wet airborne acidic species; and 4) facilitate the use of clean natural gas as a fuel switching option. The range of requirements in the 11 House and 5 Senate bills formally introduced as of late August 1984 is presented in Tables 1 and 2.(1) The various bills differ in overall emission reduction requirements, the presence or absence of emission limitations for sources, the geographical area covered, the use of a fee on electricity generation to finance much of the capital and some of the operation and maintenance costs of the controls, and the need to offset growth.

Although all the bills assume that the emission reductions will come mainly from utility and large industrial boilers, they do provide the states with flexibility in achieving their emission reduction targets. However, a few of the measures, such as the widely discussed Sikorsky-Waxman bill (H.R. 3400), would require the largest uncontrolled utility sources of SO_2 (with emissions >3 lb/million Btu)* to install devices that can meet the 1979 New Source Performance Standard (NSPS) of 70 to 90% control -- i.e., to retrofit a flue gas desulfurization (FGD) unit on each large powerplant. In general, the greater the flexibility provided by a bill, the greater the opportunity for using a mix of emission reduction strategies, such as various levels of coal washing/cleaning and oil desulfurization; wet and dry, regenerable and nonregenerable FGD; fuel switching and blending; early retirement/replacement of old, uncontrolled plants; conservation; and low-cost, moderately effective controls.

A basic feature of all the emission reduction bills is the allocation of SO_2 reduction targets to each state -- the 31 "eastern" states or all 48 contiguous states -- in proportion to the percentage of total SO_2 emissions generated by boilers in each state that emit at a higher rate than a specified threshold (1.2 or 1.5 lb/million Btu).** The states then are required to devise plans for achieving these reductions and are given the flexibility, within the constraints of the bill, to select a strategy based on their own technical, economic, and political situation. Under some bills, this feature can default to a uniform limitation of 1.2 or 1.5 lb/million Btu if a state does not develop an approvable plan. It applies to the total emission reduction allocation in most bills (e.g., S.768 by Senator Stafford) or the increment above the reductions achieved by the mandated use of FGD in the Sikorsky-Waxman bill. With this flexibility, states could, for example, direct or encourage certain sources to use dry SO_2 controls, such as limestone injection/multistage burners (LIMB), alone or combined with coal cleaning.

Intrastate trading is implicit in all bills (beyond the mandated controls), but some proposed measures provide additional flexibility by allowing interstate trading. This discretionary authority also brings opportunities for achieving the most cost-effective overall strategy through a mix of emission reduction approaches, including LIMB and other low-cost dry SO_2 techniques.

Several acid deposition bills would also enable the states to improve the cost effectiveness of their control strategies by using simultaneous SO_2/NO_x controls. These opportunities would exist with the passage of legislation that: allows NO_x/SO_2 tradeoffs (e.g., a state's SO_2 emission reduction allocation would be decreased by 1 lb SO_2/yr for every 2 lb NO_x/yr that it controls beyond

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* Use the following to convert to metric equivalents; 1 Btu = 1.055 kJ; 1 lb = 0.454 kg; and 1 ton = 907.2 kg.

** For example, if the sum of the SO_2 emissions from all boilers in state X that emit at a higher rate than 1.5 lb/million Btu is 2.5 million tons per year (TPY), these emissions would correspond to approximately 10% of the 24 million TPY generated by all sources in the 31 eastern states. Therefore, if Congress were to require a reduction of say, 8 million TPY in these 31 states, state X would be allocated a reduction of 0.1 x 8 = 0.8 million TPY.

its current state implementation plan);[2]* places a limit, or cap, on total NO_x emissions from all sources in the controlled region; and/or requires offsets for new sources. If legislation allowed, a 2:1 NO_x/SO_2 tradeoff, LIMB would be considered equivalent to a 90% efficient FGD if the LIMB system could achieve 60% reductions of both SO_2 and NO_x, or to a 75% efficient FGD if LIMB obtained only 50% control of each pollutant.

The simultaneous SO_2/NO_x control LIMB technology, if fully developed to our expectations, would be uniquely suited to take advantage of these potential flexibilities, thereby substantially reducing the potential costs of any national acid deposition emission reduction program. Furthermore, its role could become even more significant if the growing concern over a possible link between emissions and perceived forest degradation leads to legislation that further limits NO_x emissions.

EMISSION SOURCES -- OPPORTUNITIES FOR SATISFYING LEGISLATIVE MANDATES

Estimates of current and projected SO_2 and NO_x emissions are presented in Table 3 by source.[3] The projections for the year 2000 do not assume any controls (beyond current regulations) due to acid deposition legislation.** Boilers, both utility and industrial, now account for about 75% of the total SO_2 emissions, and their relative contribution would grow by the year 2000 if not controlled further. Within the utility sector, over 90% of the SO_2 emissions are generated in the eastern 31 states, and over 30% of this amount (6 to 7 million TPY) would be captured if current NSPS-type controls were applied to the 50 largest boilers (emitting above 3 lb SO_2/million Btu).[4]

Boilers, both utility and industrial, also account for nearly 50% the total NO_x emissions generated in the United States and about 85% of the total produced by stationary sources. Projected increases in the utilization of existing coal-fired utility boilers account for the growth shown for this sector.

The substantial interest demonstrated by both the political and technical communities in developing cost-effective controls for the SO_2 and NO_x emissions from boilers is quite understandable from the perspective of these emission figures. The opportunities for achieving any legislated emission reductions by a mix of control technologies, however, become clearer when one considers the wide range of boiler types and characteristics that could be affected by such legislation. The span in size, sulfur content of coal used, capacity factor, and age of just the 100 largest utility sources, as shown in Table 4, show this diversity.[5] Furthermore, an analysis by the Office of Technology Assessment (OTA) for Congressman Dingell has shown that 5 of the "top 50" utility plants have space constraints that could preclude the use of scrubbers, while 6 others may be so old (pre-1950) and/or small (<100 MWe) that they would suffer from a very poor cost-effectiveness (high cost per ton removed) if controlled by FGD.[6]

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* The 2:1 tradeoff figure is not based on effects data; therefore, this ratio may change in future legislative proposals, if retained.

** Growth projections are always uncertain and dependent on the economic assumptions used. Starting from the same base and using the same models, but with different input assumptions, some economists have projected increases (difference between 1980 and 2000) as large as twice those shown here for some sources.

ANALYSES OF CONTROL SCENARIOS

A number of government agencies, as well as the Edison Electric Institute, have commissioned comprehensive computer analyses of the potential impacts of two bills, Stafford (S.768) and Sikorsky-Waxman (H.R. 3400).[7] These analyses have used a variety of assumptions on growth, energy costs, and control cost/availability. The federal sponsors of these studies are EPA, the Department of Energy (DOE), and the Office of Technology Assessment (OTA). In addition, the Congressional Research Service (CRS) has used results from the analyses performed for these sponsors to conduct its own studies for members of Congress.

Two computer models have been used for these studies. In general, they operate by calculating the cost effectiveness of all potential emission reduction approaches (e.g., Table 5, taken from Reference 8) for each major source or source category and then selecting, through an optimization routine, that combination of approaches for all the sources/categories within specified study regions that minimizes the total costs for each region.* Alternatively, emission limits are specified for each source and a least cost option selected for that limit.

The models -- AIRCOST (adapted from AUSM [Advanced Utility Simulation Model] and operated by E. H. Pechan & Associates) and CEUM (Coal and Electric Utilities Model by ICF, Inc.) -- differ primarily in their algorithms for projecting energy usage patterns and making fuel choices (e.g., between cleaned coal, FGD with conventional coal, or natural gas). Other differences include the detail in treatment of industrial sources and the provision to simulate the selective use of lower emitting plants, early retirements, replacements, growth, and phased timing of implementation.

By and large the emission inventories come from reports to DOE's Energy Information System (EIS) for utilities and from EPA's National Emissions Data System (NEDS) for nonutility sources. However, the various modelers have interpreted some of these data based on other EIS surveys and their own information/data banks. As noted earlier, the biggest differences probably are found in the growth projection approaches. A common thread to all the models (except when used to study the impacts of specified emission limits) is that they assume "a perfect market" for the exchange of emission reduction obligations within a state. Hence, the resulting costs may be considered a lower bound estimate (to the extent that other assumptions do not compensate for this analysis approach).

These models have been used to determine the potential costs, state and national emission reductions, coal production (miner employment) impacts, and the demand for FGD installations of the Sikorsky-Waxman and Stafford bills.

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* A study region can be a state or 1 of the 47 "demand regions" used by one model.

Variations on the basic analyses have included intrastate trading, interstate trading, restrictions requiring the continued use of local coal, and various specified, uniformly applied emission limits (e.g., 1.5 lb SO_2/million Btu). In most cases the primary control technologies considered were coal switching and FGD.

Typical results from such analyses are shown in Figure 1.(9) This figure depicts the range of annualized costs estimated by a number of studies for control programs that legislate various levels of SO_2 emission reductions from the 31 eastern states (with the protocol for allocating reductions to each state as described earlier). The relationships between the different studies do not follow an expected or consistent pattern -- e.g., the results prepared for the energy organizations are consistently higher or lower than those prepared for EPA or OTA. Furthermore, the results from a single model (e.g., ICF's model) can vary as much between applications as they do in comparison to other models, depending on the scenarios and input assumptions.* Nevertheless, all the results (for a given emission reduction target) agree to within ± 50% at the lower emission reduction levels and ± 25% at the upper levels. As a point of reference, it should be noted that a 1.5 mills/kWh charge on all electric energy production by fossil fuels in the United States would generate a revenue stream of approximately $3 billion/yr.(10)

A similar analysis was conducted, with slightly different assumptions, to assess the potential cost difference to utilities between a control strategy that specified the use of FGD (e.g., for regulatory expediency or to avoid dislocation of miners) and one that allows each source to choose the most cost-effective approach for achieving the specified limitation.(11) Key results from this analysis are presented in Table 6.** In general, switching to a low sulfur coal is cheaper than installing FGD (one of the models allows the local price of low sulfur coal to rise in response to market forces due to increased consumption by the utilities), but local facility constraints and coal supply conditions may cause FGD to be the most cost-effective option in some cases. Again, as a point of reference, if a nationwide fee were used to support the control program, the differential between the two strategies at a limit of 1.5 lb SO_2/million Btu (which would result in an 8 million TPY reduction in the eastern 31 states) would require a fee increase of approximately 0.4 to 0.7 mills/kWh for a total national charge of between 0.9 and 1.2 mills/kWh to about 1.6 mills/kWh.

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* Utility estimates or rate increases needed to offset the costs of acid deposition control programs, in the absence of national support from a fee, range from 4 to 26%. These estimates assume an amortization period of 5 years versus 20 years used by EPA and OTA (based on the expected life of the equipment).(12)

** The results in Table 6 for the "FGD specified" case fall within the band of results in Figure 1.

CONTROL TECHNOLOGY -- THE LIMB PROGRAM

The subject of control technology is a logical follow-up to the previous analysis of control scenarios. Although fuel switching, clean coal and FGD, and LIMB are considered as technology options, only LIMB is considered an emerging, new technology. The others are considered to be well established, commercially available technologies. For these reasons, only the LIMB technology is discussed here.

As shown in Figure 2, Limestone Injection/Multistage Burners (LIMB) is an EPA-sponsored effort to develop an effective and inexpensive emission control technology for pulverized coal boilers that will simultaneously remove SO_2 and NO_x from boiler flue gases. LIMB combines sorbent injection for SO_2 control with low NO_x burners for NO_x control. The concept of sorbent injection into furnaces for SO_2 control is not new. In the early development (1965-early 1970's) of SO_2 control technology, it was one of the alternatives considered for achieving moderate to high removal efficiency at low cost. Extensive testing was carried out with limited success. As shown in Figure 3, plant-scale SO_2 removals ranged from 20 to 50% at reasonable sorbent loadings (i.e., about calcium to sulfur molar ratio of 2).[13] The reasons most commonly quoted for low performance were: 1) high temperature deadburning and decomposition of the sorbent sulfur complex, and 2) inefficient mixing of sorbent with combustion gases. Interest in the technology was revived as a result of extensive development work on low-NO_x burners, and in 1979 a short series of trials sponsored by EPA achieved SO_2 removals up to 70% with limestone injection through an advanced low-NO_x burner at a calcium to sulfur molar ratio of 2.[14] Data points for these trials are also presented in Figure 3. The limited pilot scale data was encouraging, and an additional strong incentive for further development emerged from an assessment of strategies available for retrofit control of acid rain precursors. A brief summary of the technology follows.

Low-NO_x burners of various designs have been developed by both EPA and private industry. Low-NO_x burners are designed so that combustion air is added in a staged manner ensuring a fuel rich zone early in the combustion process. This zone, which is chemically reducing, tends to effectively reduce NO_x production associated with oxidation of the nitrogen in the fuel and combustion air. Figure 4 illustrates the low-NO_x burner concept and shows how combustion air is added in a staged sequence with the coal (primary air), then, through annular entry ports (secondary air), and finally completing combustion through tertiary air ports.

The SO_2 control and, in fact, the LIMB concept, is based on the addition of an alkali material such as limestone in conjunction with low-NO_x (multistage) burners. The sorbent (limestone or other alkaline material) is injected directly into the furnace and subsequently reacts with gas phase SO_2 to form dry calcium sulfate which is removed, with the flyash, in a particulate collection device. Figures 5 and 6 present the LIMB technical background and a generic design of an integrated LIMB system, respectively.

LIMB Applicability

The relative simplicity of the technology lends itself to a relatively low cost retrofit on a wide variety of systems. Since only about 10% of the coal-fired boiler capacity east of the Mississippi River are subject to NSPS controls for SO_2 and NO_x, any significant reduction in these pollutants requires a retrofit of existing boilers which may have a remaining useful life of from 5 to 30 years or more. The most important consideration in actual applicability on any specific boiler is the time/temperature history which will determine the degree of sulfur control for a given sorbent. The second most important factor is the firing system (i.e., wall- or tangentially-fired) which will affect the ability to inject and mix the sorbent with the combustion gases at the right condition. These factors (and others) will be discussed later.

Overall Objective and Technical Goals

The objective of the LIMB technology program is to demonstrate and commercialize the technology at an early date for both wall- and tangentially-fired boilers. The performance goals within this objective are: 1) for retrofit, 50-60% reduction of both SO_2 and NO_x from uncontrolled levels; 2) for new systems, 70-80% NO_x reduction and 70-90% SO_2 removal from uncontrolled levels; and 3) achievement of these goals at costs at least $100/kWh less than the major technology alternative, FGD, and 30% to 50% less than the cost of FGD on a per ton of sulfur removal basis.

The LIMB Research and Development Program(15)

The LIMB program has been structured to give the best possibility of achieving the stated goals with applicability to the major portion of the existing boiler population. The major research objective is to provide the basis for widespread private sector commercialization based on successful demonstration on both a wall- and a tangentially-fired boiler. An essential supporting objective is to perform the generic R&D necessary to ensure success of the demonstrations and to maximize the sulfur capture potential of the technology. Other supporting objectives are to integrate and generalize the R&D results with those from the demonstrations into a design methodology for assessing applicability to any given boiler and to improve the SO_2 removal efficiency to 70-90% for new sources and possible retrofit in selected cases. To achieve these goals, activity has been concentrated in five major areas, as discussed below.

I. Development and Demonstration on Wall-Fired Boilers - Wall-fired boilers are one of the two major types of boilers and are sold by three manufacturers; Babcock & Wilcox, Foster-Wheeler, and Riley-Stoker. The wall-fired boiler has been the subject of the initial LIMB development because both the R&D background and large scale experimental facilities were available. The demonstration on a representative wall-fired boiler was initiated the end of September 1984. Babcock & Wilcox Company will install LIMB on a 105 MW single-wall-fired unit at the Edgewater Station of Ohio Edison Company.

The final site-specific design for the installation will be completed in August 1985-February 1986. Long term testing will begin July 1987, and a report documenting the performance evaluation will be completed by March 1989.

II. Development and Demonstration of Tangential Boiler Technology - Tangentially-fired (T-fired) boilers are the second major class of boilers and are manufactured by Combustion Engineering. These boilers, which constitute nearly half of the installed utility capacity in the U.S., have significantly different firing systems and combustion conditions than wall-fired boilers. As a result, a successful wall-fired demonstration does not directly provide a basis for application to tangentially-fired systems and a T-fired demonstration demonstration is considered necessary to ensure the potential commercialization of LIMB for both major boiler types. Although pilot scale work has been initiated, development for these systems is lagging the wall-fired technology by about 2 years. Specific R&D will provide the basis for initiation of a full-scale demonstration in FY 87, and the long term performance would be documented in FY 91. The generic R&D results provide the basis for application of LIMB to T-fired boilers, and limited system-specific development has been done. One key factor in obtaining acceptable SO_2 capture is injecting and mixing the sorbent at the proper combustion conditions. The injection and mixing of sorbents is complicated by the vortex action produced in the combustion gases by T-firing. To date, only limited small pilot scale development has been performed at representative T-fired combustion conditions. Further work will be done at the pilot and prototype scales to scale up the sorbent injection and mixing technology.

III. Generic Research and Development - R&D of this type is directed toward a complete understanding of the process and is relatively independent of the hardware-specific constraints of practical boilers. It provides information essential for application of LIMB to all boiler designs. The R&D has provided insight on the effects of critical process parameters on SO_2 capture. It has shown how these parameters affect sorbent activation and subsequent sulfur capture as a function of combustion system conditions. It has also provided an understanding of f)yash/sorbent mixture characteristics as related to slagging, fouling, and particulate capture. As a result of these findings, it has been concluded that limestone alone will not achieve the LIMB sulfur capture goals for many units in the U.S. boiler population. However, it has also provided at least two alternate sorbent approaches capable of meeting or substantially exceeding the goal of 50-60% capture. Major R&D areas, results, and planned activities are discussed below.

1. In-house research has identified increased sorbent surface area as a key factor in obtaining high sulfur capture. It has been shown that high surface area can be generated external to the combustion process and/or in situ. These high surface area sorbents have shown the potential for sulfur capture in excess of 70%. The planned R&D addresses methods for obtaining highly reactive sorbents, for optimizing reaction conditions to achieve maximum capture, and for minimizing sorbent costs.

2. Another key factor is the interaction of sorbents with mineral matter which can either enhance or degrade the sorbent reactivity. The most promising results indicate that it may be possible to add small amounts of relatively inexpensive, innocuous promoters (mineral compounds) which will enhance the sorbent activity. Sulfur captures approaching those of high surface area sorbents have been achieved with promoted limestone in limited bench scale experiments. It also appears that promoters can significantly improve the performance of high surface area sorbents. A significant effort is necessary to understand the enhancement mechanisms and to provide the basis for use in practical systems. It should be noted that a similar understanding is necessary for other sorbent/mineral matter interactions which can inhibit sulfur capture and which affect slagging, fouling, and collection characteristics of the particulate.

3. Process analysis has indicated substantial benefits may be derived from recycle of unreacted sorbent and promoters. In addition, utilization of the spent sorbent and flyash has significant potential economic benefits. Pilot scale R&D is planned to evaluate the engineering feasibility of these process options.

4. Extensive prototype scale testing of wall-fired boiler low-NO_x burners has been conducted to evaluate sulfur capture potential with injection of conventional sorbents. A substantial data base exists for both NO_x and SO_2 control potential of a number of experimental and commercial burners. Work is planned for scale-up of the improved performance sorbents and for evaluating factors related to tangentially-fired boiler applications. This testing will address criteria for injection of high activity sorbents into a thermal environment representative of all U.S. boilers. The testing on wall-fired prototypes will build directly on previous experience with a wide variety of burner designs. The optimum injection locations will be selected for each class of sorbents based on smaller scale R&D. Injector designs will be evaluated and scale-up criteria developed. Prototype testing for tangentially-fired systems will be initiated to examine design features in the presence of a vortex flow field. Both cold flow modelling and large scale combustion tests are planned. Finally, an EPA/industry cooperative program of testing on a small boiler (20-40 MW) will be initiated to examine both sulfur capture and operability/reliability impacts. Flexible operation, including types of fuels and sorbents, will provide an attractive R&D complement to full-scale boiler demonstrations. It may also allow an assessment of applicability of LIMB to industrial boilers.

5. Analytical support including specialized measurements, which are required for LIMB R&D and demonstrations, is also provided in this area. These on-going activities include routine and developmental analyses for sorbent characteristics and LIMB particulate form.

In summary, R&D has shown the potential for improved sulfur capture but it has not completely provided the necessary understanding for application. Since improved sulfur capture and other improvements will significantly enhance both the applicability of LIMB to the U.S. boiler population and its economic advantage over FGD, generic R&D is expected to continue along with R&D to support the solution of specific problems which may be encountered in the demonstration program.

IV. Generalization of the Technology - For ultimate widespread use of the LIMB technology, the R&D results must be integrated with full-scale boiler demonstration results to provide a well defined set of criteria for application of LIMB to a wide range of boiler designs, coals, and sorbents as guidance for commercialization by the private sector. A limited number of demonstrations alone may not be sufficient for widespread private sector commercialization. This element of the program includes both process analysis to evaluate applicability and economics for specific systems, and process modelling, with supporting measurements on operating boilers, to provide a methodology useful for site-specific design decisions. Process analysis has emphasized LIMB system options for application to different boiler cases and for minimizing the cost per unit SO_2 removal. Process modelling will continue to provide component models for thermal history, sorbent activation and reaction, injection, and mixing. Integration of these component models into an overall design tool is planned.

V. New Boiler Applications - This area represents an extension of the existing program. As stated earlier, the performance goal for new systems is 70-90% SO_2 reduction from uncontrolled levels. The sulfur capture potential of LIMB may be improved to this range in three ways: 1) increased sorbent activity through higher surface area and/or the use of promoters; 2) use of residual sorbent activity in combined techniques; and 3) modification of boiler design. Current emphasis has been on retrofit applications, but all three could be applied to the design of a new system with a high probability of success. R&D on pilot and prototype scale equipment simulating a new boiler would be required to verify the potential. This is not planned in the current program.

In prior sections, emission sources and analysis of control scenarios were discussed. Having just covered control technology, it is appropriate to see how fuel switching, clean coal, FGD, and LIMB technologies seem to fit into implementation of various acid deposition strategies calling for emissions reductions. The implications of different control strategies on these technologies are discussed below.

IMPLICATIONS OF DIFFERENT ACID DEPOSITION CONTROL STRATEGIES ON CONTROL TECHNOLOGY UTILIZATION

Analyses have shown that LIMB could reduce the total costs of meeting specified national emissions reduction targets. The extent to which LIMB might be employed and the cost savings it could bring to an emission reduction program depend primarily on the total emissions reduction target, the existence of a mandate to use FGD on the largest sources, the freedom to switch to lower sulfur coal, and, of course, the eventual effectiveness of dry SO_2 control systems. For example, an analysis performed by the Congressional Research Service of the Library of Congress projected 20 to 35% savings in capital costs if LIMB were available and coal switching not allowed.(16) This analysis, whose results are shown in Table 7, based its emissions reduction strategy on the control of all utility boilers in the 31 eastern states

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* The purpose of this analysis was to investigate the economics of user fees to support the capital costs of technological controls, thereby overcoming the projected cost advantages of coal switching. Therefore, the analysis emphasizes capital costs and precludes coal switching as a strategy.

whose primary fuel is coal with a sulfur content greater than 1.5%. It also allowed NO_x reductions to be substituted for SO_2 reductions at a 2:1 rate (i.e., every 2 lb of NO_x controlled counted as 1 lb of SO_2). Further, the analysis assumed that all the NO_x and SO_2 emissions reduction schemes shown in Table 7 (except FGD) would be applied at their indicated effectiveness to about 50% of the total units available, and that FGD would be used only as needed to achieve the desired total emissions reductions.

For the "current technology" scenario presented in Table 7, the analysis projects that low-NO_x burners, physical coal cleaning, and lime spray drying could remove 4.5 million TPY of SO_2 equivalent (i.e., SO_2 plus NO_x at 2:1), while FGD would eliminate the remaining 3.5 million TPY. With the "current technology" plus LIMB, 3.0 million TPY of the reductions otherwise achieved by FGD would come from the use of this newer technology. At 8 million TPY total SO_2 equivalent reduction without coal switching, a control program using LIMB could require about 35% less capital than one without LIMB ($14.6 instead of $22.3 billion). According to the analysis, FGD would always be required for reductions beyond 8 million TPY and would add approximately $3.1 billion to the total program costs per additional million TPY.

When coal switching is allowed, the results are slightly different but also show an overall cost benefit with LIMB under certain conditions. Table 8 gives a projection of the cost savings that could accrue under the Stafford bill (S.768, requiring 8 million TPY reduction in 10 years, allowing intrastate trading but no NO_x/SO_2 tradeoff, and placing neither requirements on the use of FGD nor restrictions against coal switching) if LIMB were to be demonstrated at 50 or 60% SO_2 removal.[17] No credit is given in this analysis for the associated NO_x removal, and the technology is applied only to utility power plants. To bound the analysis, the investigators also assumed that the more efficient LIMB system would be twice as reliable as the 50% effective technology. As Table 8 shows, LIMB may not have a significant impact on utility control strategies at an emission reduction of 8 million TPY if it is only 50% efficient. Because it is usually more costly to achieve the required SO_2 reductions with LIMB at this removal rate than to switch to low-sulfur coal, most utilities would be expected to opt for a coal switching approach. Therefore, the availability of LIMB at this level of performance is not expected to have a significant impact on the total costs of the 31-state SO_2 reduction program, its cost effectiveness, or the costs per kilowatt hour generated (i.e., the average electricity rate increase that would be needed to offset these costs).

At 60% efficiency, LIMB would have a significant penetration and could reduce projected annual control costs by 20%. In many instances, a 60% efficient LIMB system represents a less costly control option than switching to low-sulfur coals. For some other boilers, LIMB at this SO_2 removal rate can also be more cost effective than FGD. As a consequence, LIMB could be used to treat 57 GW of capacity, mostly in lieu of coal switching but also by reducing the need for FGD from 8 GW to 2 GW. This substantial predicted increase in the use of LIMB would raise the cumulative capital costs of this 31-state SO_2 reduction program from $2.6 billion (1982) without LIMB to approximately $4.3 billion with LIMB despite the overall projected reduction in annualized costs. The lower capital costs assumed for LIMB relative to retrofit FGD (by a factor of 6 on a dollars/kilowatt basis) can compensate only partially for the substantial increase in capacity that would be treated with LIMB.

Analyses of similar SO_2 reduction programs, but with 31-state targets ranging from 2 to 12 million TPY, suggest that LIMB at 60% SO_2 removal may be a viable option for utility boilers under control strategies that require between 4 and 8 million TPY SO_2 reductions.[18] At lesser reduction requirements, shifting to lower sulfur coal is more cost-effective; while at higher reductions, only FGD could achieve the necessary control levels (85 to 90% for virtually all affected boilers). This finding, which is depicted qualitatively in Figure 7, is restricted to the scenario used in the analysis; namely, no attempt to apply LIMB to industrial boilers or give any credit for the associated NO_x reduction, or actually require NO_x reductions. If industrial boilers adopt the LIMB technology and/or low-NO_x reductions are encouraged or mandated, LIMB could have a significantly greater impact than indicated by this analysis.

IMPLICATIONS OF LEGISLATIVE ALTERNATIVES

Although it is unclear if or when Congress might enact legislation that requires SO_2 and/or NO_x reductions under an acid deposition or forest protection program, it does seem safe to predict that any such legislation would result in strategies that could benefit from cost-effective, moderately efficient control technologies. Since LIMB or other low-cost dry SO_2 systems are expected to be substantially less capital intensive than FGD, but might be less competitive in their utilization of sorbent, these control options may provide the most cost-effective solution for boilers that:

- Burn low- or moderate-sulfur coal,
- Are nearing the end of their usual life (and are not candidates for life extension),
- Have space constraints that would significantly increase the costs of an FGD retrofit, or
- Operate at a relatively low utilization factor.

These same technologies would play an increasingly important role in regionally optimized control strategies at lower overall emission reduction targets -- e.g., at the 6 to 8 million TPY level -- or if NO_x reductions are required or credited (through NO_x/SO_2 tradeoff allowances). Furthermore, if LIMB and similar dry SO_2 controls are considered cost-effective for small utility boilers, they should be at least as good for industrial boilers, which could be targets for control for two reasons: to help a state achieve its allocated emission reductions and/or to provide offsets for growth.

One result stands out clearly from the analyses conducted by EPA and other agencies on potential acid deposition control strategies: under virtually all potential legislative mandates and resulting control strategies, low-cost, moderately effective control technologies like LIMB can reduce the total annualized costs of achieving the legislated goals. The ability of these control systems to effectively perform the key role they should assume will, however, depend on cooperation with industry boiler manufacturers, architectural and engineering organizations, boiler owner/operators, and others.

ACKNOWLEDGEMENT

The writer wishes to acknowledge George Offen of the Acurex Corporation for his competent and timely assistance in the preparation of this paper. Dr. Offen is currently with the Electric Power Research Institute (EPRI).

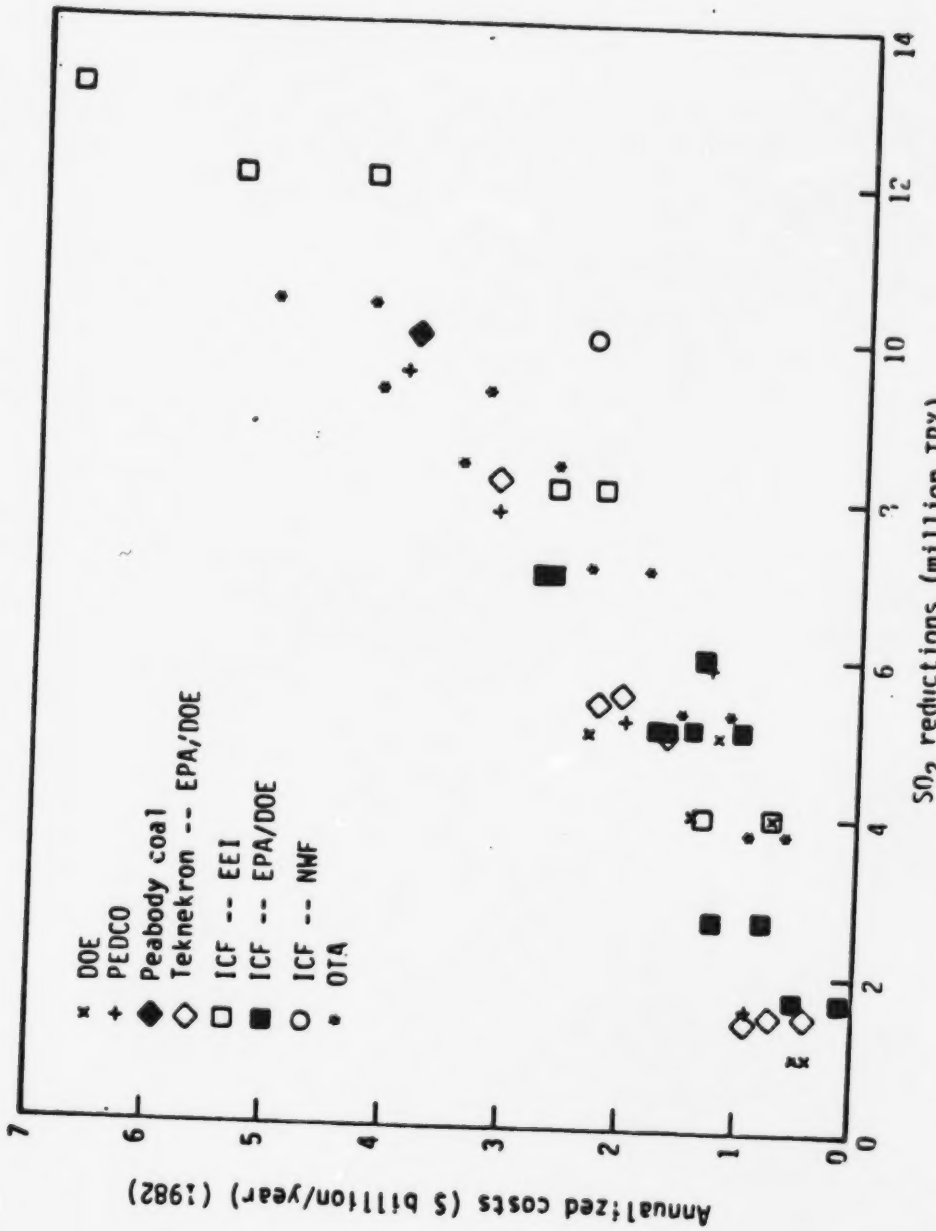


FIGURE 1. RANGE OF ANNUALIZED UTILITY SO_2 CONTROL COSTS.(9)

- THE LOW NO_X BURNER PROGAM IS AN EPA EFFORT TO DEVELOP SECOND-GENERATION COAL BURNERS AND COMBUSTION SYSTEMS CAPABLE OF REDUCING NO_X EMISSIONS FROM COAL-FIRED UTILITY AND INDUSTRIAL BOILERS.

- THE LIMB PROGRAM IS AN EPA EFFORT TO DEVELOP EFFECTIVE AND INEXPENSIVE EMISSION CONTROL TECHNOLOGY FOR COAL-FIRED BOILERS THAT WILL REDUCE SULFUR DIOXIDE (SO_2) AND NITROGEN OXIDES (NO_X). THE LIMB CONCEPT UTILIZES LOW NO_X BURNERS TO INTRODUCE LIMESTONE FOR SO_2 REMOVAL IN THE BOILER COMBUSTION ZONE.

- LIMB TECHNOLOGY REPRESENTS A LOW-COST ALTERNATIVE TO CURRENTLY AVAILABLE SO_2 CONTROL APPROAHCES: FLUE GAS DESULFURIZATION, COAL CLEANING, AND COAL SWITCHING.

- LIMB TECHNOLOGY IS ATTRACTIVE IF COAL COMBUSTORS MUST BE CONTROLLED TO MINIMIZE EMISSIONS OF ACID RAIN PRECURSORS, BECAUSE LIMB IS EASILY RETROFITTED TO LARGE AND SMALL COAL-FIRED BOILERS, IS LOWER IN COST THAN ANY AVAILABLE ALTERNATIVE, AND CAN ACHIEVE CONTROL OF BOTH SO_2 AND NO_X -- THE TWO MAJOR ACID RAIN PRECURSORS.

FIGURE 2. THE LIMB/LOW NO_X BURNER PROGRAM.

Sorbent Injection – Background

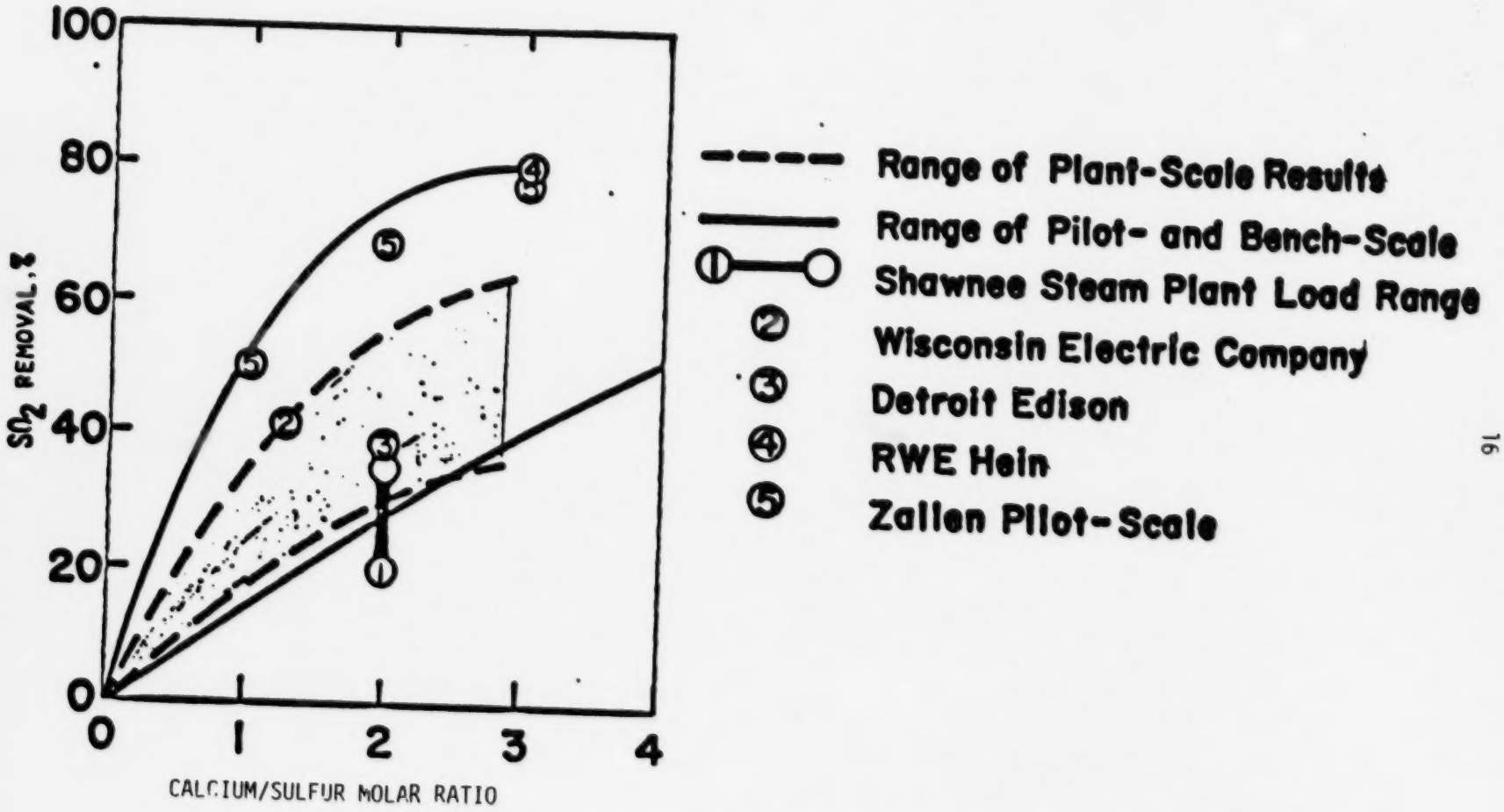


FIGURE 3. RANGE OF PILOT AND BENCH SCALE STUDIES.

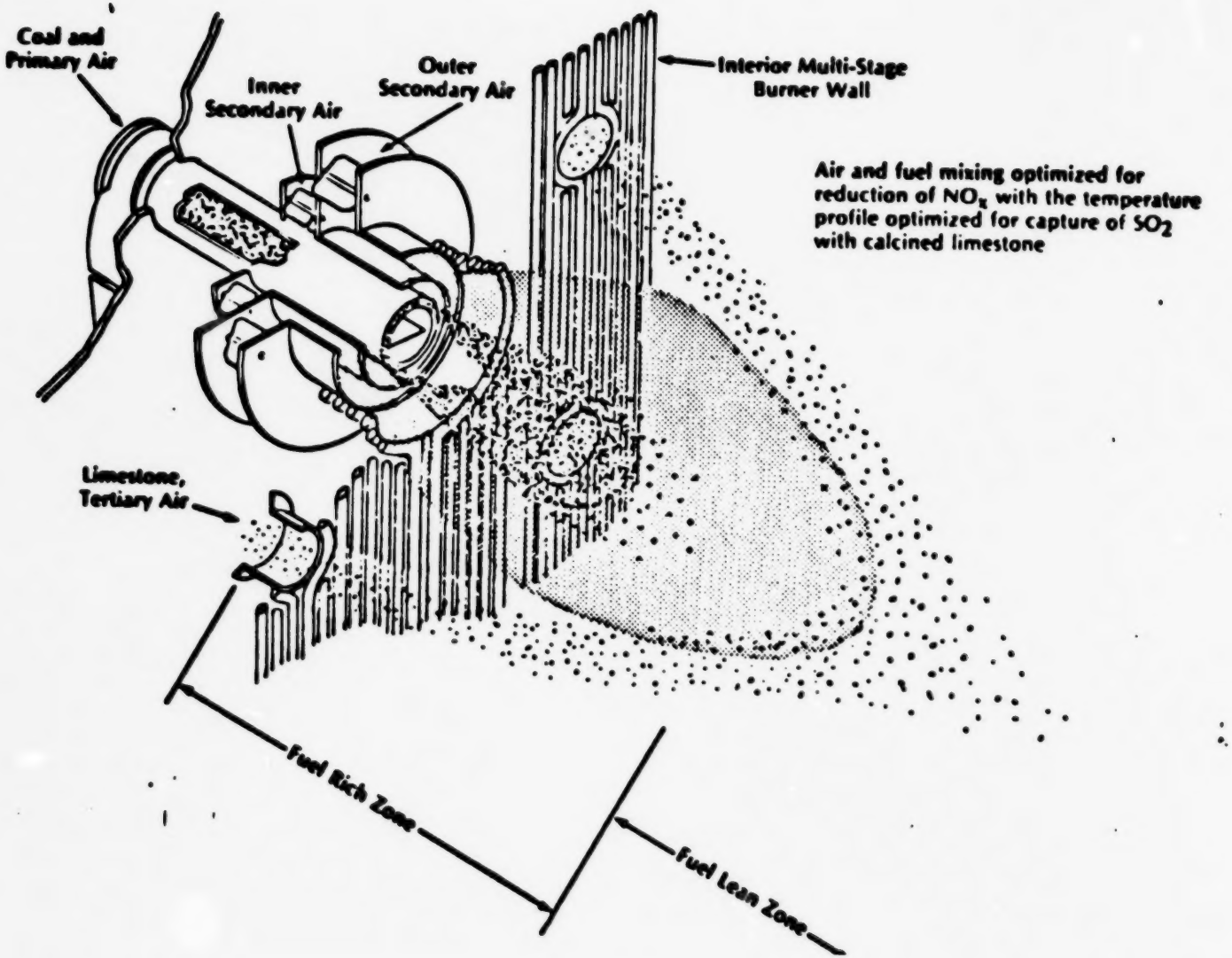
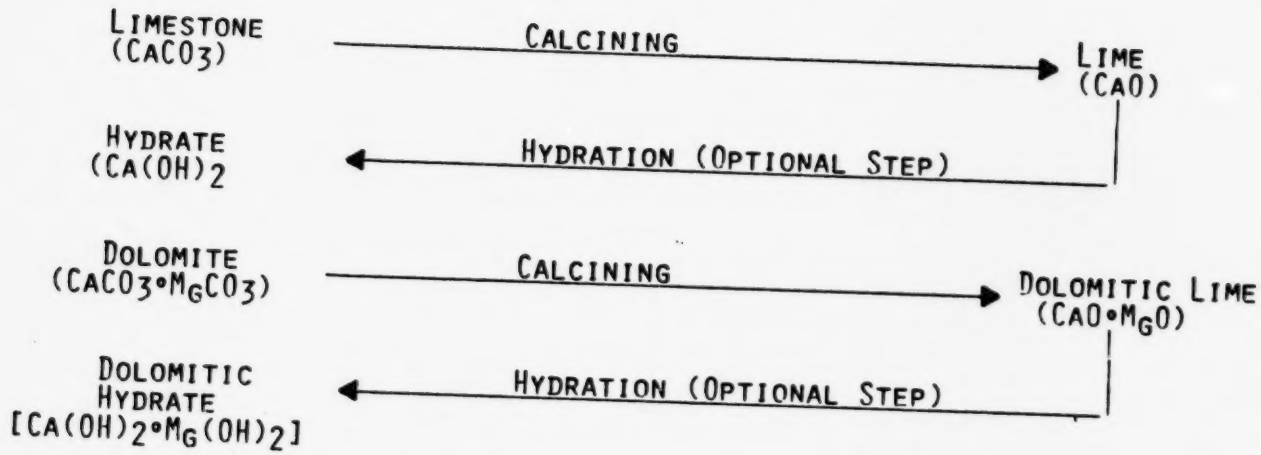

Coal and Primary Air
Inner Secondary Air
Outer Secondary Air
Interior Multi-Stage Burner Wall
Air and fuel mixing optimized for reduction of NO_x with the temperature profile optimized for capture of SO_2 with calcined limestone
Limestone, Tertiary Air
Fuel Rich Zone
Fuel Lean Zone

FIGURE 4. LIMESTONE INJECTION MULTISTAGE BURNER FOR SIMULTANEOUS NO_x AND SO_2 CONTROL

SORBENTS



LIMB REACTION

$$CaO + SO_2 + 1/2\ O_2 \longrightarrow CaSO_4$$

(MgO IN DOLOMITE IS ESSENTIALLY UNREACTIVE)

Ca/S RATIO

MOLES OF SORBENT CALCIUM DIVIDED BY MOLES S IN INCOMING SO_2

FIGURE 5. LIMB TECHNICAL BACKGROUND.

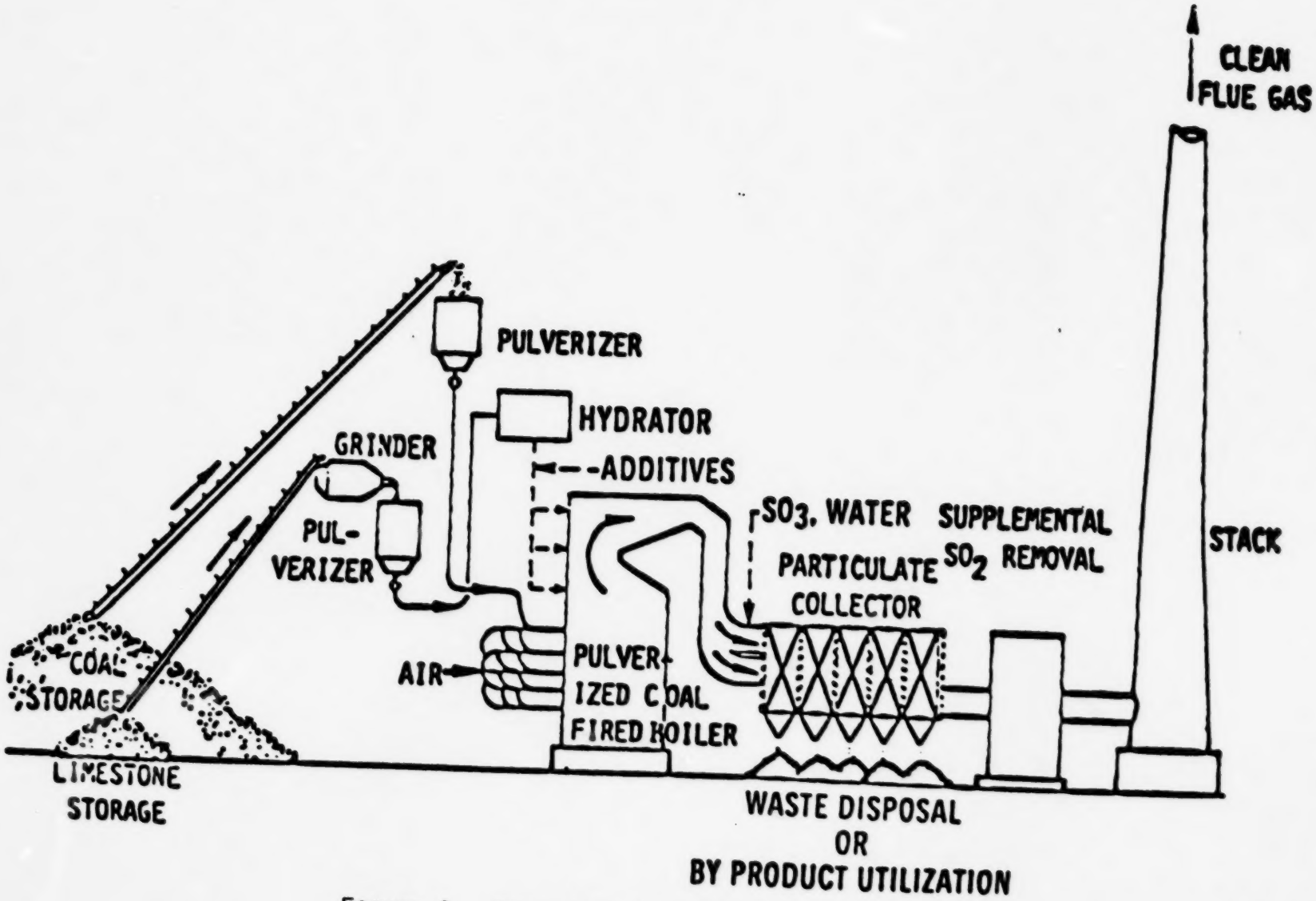


FIGURE 6. SCHEMATIC OF INTEGRATED LIMB SYSTEM.

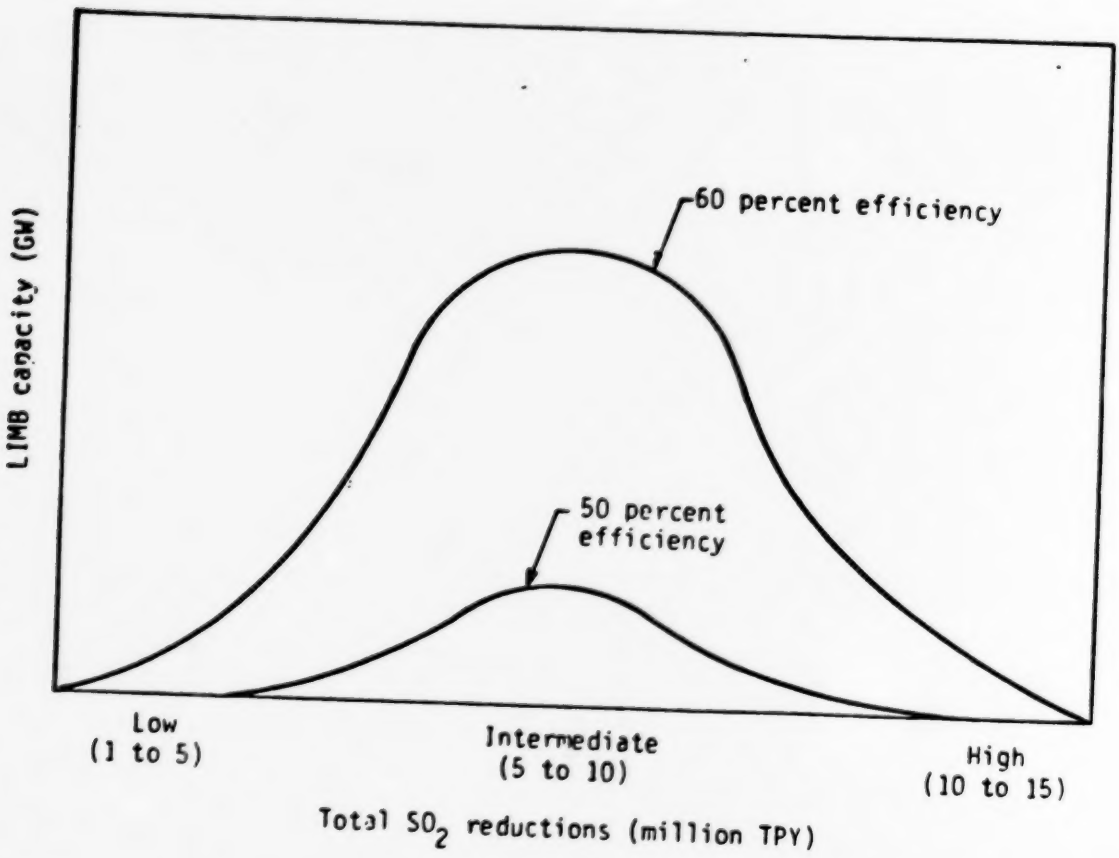


FIGURE 7. QUALITATIVE PERSPECTIVE OF POTENTIAL LIMB PENETRATION INTO THE UTILITY SECTOR UNDER THE STAFFORD BILL (S.768). (15)

TABLE 1. RANGE OF LEGISLATIVE STRATEGIES

- SO_2 emission reductions
  - -- Global: 8 to 12 million tons/yr (below 1980 levels)
  - -- Specific
    - 50 largest uncontrolled coal-fired powerplants emitting >3 lb/million Btu to install FGD
      or
    - Large sources limited to 1.2 to 1.5 lb/million Btu
      or
    - Reductions allocated by each state -- sometimes with constraints on coal switching
- NO_x requirements
  - -- More stringent NSPS for coal-fired utilities (e.g., H. R. 3400/ Sikorsky-Waxman)
  - -- Limit (cap) on total NO_x emissions (e.g., S. 768/Stafford)
  - -- More stringent limits on vehicles (H. R. 3400/Sikorsky-Waxman)
- NO_x/SO_2 tradeoffs allowed in some bills (2:1)
- Compliance dates -- 10 to 15 years (mostly 10)
- Applicability -- mostly 31 eastern states; some 48 contiguous states
- Growth
  - -- Offsets
    or
  - -- No offsets plus exemptions for increased utilization

TABLE 2. RELATED LEGISLATIVE FEATURES

- Emission reductions allocated to states
  - -- Based on percent of total emissions in target region (31 or 48 states) generated within state by sources emitting above threshold (1.2 or 1.5 lb/million Btu)
  - -- Some bills allow interstate trading
- Financing (included in some bills)
  - -- 1.0 to 3.0 mills/kWh tax on fossil electricity generation to finance controls in lieu of local rate increases
    - 70 to 90 percent for capital costs
    - 0 to 50 percent for O&M costs
  - -- Larger support and/or tax credits for innovative controls (e.g., LIMB)

TABLE 3. CURRENT AND PROJECTED EMISSIONS OF SO_2 AND NO_x (U.S. TOTAL, MILLION TONS/YR)

	SO_2		NO_2	
	1980	2000	1980	2000
Electric utilities	17.4	17.9	6.2	9.6
(Eastern 31 states)	(16.0)	(16.1)	--	--
(Western states)	(1.4)	(1.8)	--	--
Industry	7.4[a]	9.4[a]	4.6[b]	5.6[b]
Transporation	0.9	1.0	9.4	10.7
Residential/commercial	0.9	1.1	0.8	0.7
Total U.S.	26.6	29.4	21.3[c]	26.6

Source: Reference 3.

[a] In 1980 boilers and process heaters accounted for approximately 35% of the industrial SO_2 emissions. By 2000 these sources are projected to contribute as much as 75% of the enlarged total from this sector.
[b] Boilers and process heaters contribute about 80% of the NO_2 emitted by industrial sources. This ratio is projected to remain the same through the year 2000.
[c] Includes 0.3 million tons/yr for miscellaneous sources in 1980.

TABLE 4. CHARACTERISTICS OF 100 LARGEST UTILITY SO_2 SOURCES

	Range	Average
Plant size, MW	90 to 3,300	1,000
Fuel sulfur, lb/million Btu	1.0 to 7.7	3.4
Current utilization, percent	0.23 to 0.84	0.5
Remaining unit life (assuming 40-year life)	4 to 38	22

Source: Reference 5.

TABLE 5. CONTROL TECHNOLOGY OPTIONS FOR POTENTIAL ACID DEPOSITION REDUCTION PROGRAMS

Control technology	Reduction efficiencies (percent)	Revenue requirements (mills/kWh)	Stage of development
SO_2			
Fuel-switching	30 to 90	0 to 7	In use
Physical coal cleaning	5 to 40	1 to 5	In use
Chemical coal cleaning	60 to 85	NA	Emerging
Wet flue gas desulfurization	70 to 95	10 to 17	In use
Dry flue gas desulfurization	40 to 90	9 to 15	In use
Regenerable flue gas desulfurization	70 to 90	12 to 25	Available
Oil desulfurization			
Indirect	30 to 40	4 to 6	In use
Direct	70 to 90	NA	In use
NO_x			
Low-NO_x burner -- commercial	30 to 50	0 to 3	In use
Low-NO_x burner -- developmental	50 to 80	0 to 3	Emerging
Thermal DeNO_x	50 to 65	NA	In use
Flue gas treatment without catalyst	35 to 40	NA	Available
Flue gas treatment with catalyst	80 to 90	NA	Available
Combined SO_2/NO_x			
Limestone injection multistage burner			
SO_2	50 to 90	3 to 5	Emerging
NO_x	50 to 70	3 to 5	Emerging
Fluidized bed combustion			
SO_2	<90	NA	Emerging
NO_x	20 to 30	NA	Emerging

Source: Office of Technology Assessment, primarily from EPA estimates (from Reference 8)

NA -- Not available.

Table 6. UTILITY COSTS IN 31-STATE REGION WITH AND WITHOUT MANDATED FGD (STAFFORD BILL, S.768, SO_2 ONLY)

Emission limitation (lb SO_2/million Btu)	Total SO_2 emission reductions[a] (million TPY)		Total utility costs ($ billion/yr)		Equivalent national charge (mills/kWh)	
	Utilities	All boilers	Utility choice	FGD specified	Utility choice	FGD specified
2.5	4.6	5.1	0.6 to 0.9	1.4	0.3 to 0.5	0.7
2.0	6.2	6.9	1.1 to 1.5	2.0	0.5 to 0.8	1.0
1.5	8.0	9.0	1.8 to 2.3	3.1	0.9 to 1.2	1.6
1.0	10.3	11.9	3.2 to 4.1	4.8	1.6 to 2.0	2.5

[a] Boilers in remaining 17 contiguous states add only 0.1 to 0.3 million TPY to the total reductions.
Source: Reference 12.

TABLE 7. POTENTIAL IMPACT OF LIMB ON CAPITAL COSTS OF 8 MILLION TPY SO_2 EQUIVALENT REDUCTION PROGRAM (NO COAL SWITCHING ALLOWED)

Technology	Assumed emission reduction effectiveness (%)		Unit capital cost ($/kW)[a]	Current technology		Current technology plus LIMB	
	SO_2	NO_x		Reduction (million TPY)	Cost ($ billion)[a]	Reduction (million TPY)	Cost ($ billion)[a]
LIMB	50	50	37	0.0	0.0	3.0	1.7
Low-NO_x burners	--	60	7	0.5	1.0	0.5	1.0
Physical coal cleaning	20	--	46	1.0	2.0	1.0	2.0
Lime spray drying	75	--	190	3.0	8.3	3.0	8.3
FGD	90	--	260	3.5	11.0	0.5	1.6
TOTALS				8.0	22.3	8.0	14.6

[a]December 1982 dollars.

Source: Reference 16.

TABLE 8. POTENTIAL IMPACT OF LIMB ON PROJECTED COSTS IN 1995 (1982 DOLLARS) (STAFFORD BILL, S.768, SO_2 ONLY)

		LIMB	
	No LIMB	50 percent efficient	60 percent efficient
Total cost, billion $/yr	3.5	3.3	2.8
Cost effectiveness, $/ton SO_2	320	300	240
Capital costs, billion $	2.6	2.7	4.3
Electricity rate increases, %	2.5	2.4	2.0
Utility capacity cleaned, GW			
LIMB	--	15	57
FGD	8	5	2

Source: Reference 17.

REFERENCES

1. The 11 House and 5 Senate acid deposition bills with control technology provisions (August 1984) are:

H.R.	132	Gregg (similar to S.145 Mitchell)
H.R.	2794	St. Germain (House verison of S.145)
H.R.	3251	D'Amours
H.R.	3400	Sikorsky-Waxman
H.R.	4401	D'Amours
H.R.	4906	Rinaldo
H.R.	5314	Waxman (the acid rain portion of this bill is identical to H.R. 3400)
H.R.	5370	Udall
H.R.	5590	Green
H.R.	5794	Eckart
H.R.	5970	Vento
S.	145	Mitchell
S.	768	Stafford (8 MTPY) (previous version known as S. 3041)
S.	769	Stafford (12 MTPY version)
S.	2001	Durenberger
S.	2215	Glenn

S.454 (Byrd) and S.766 (Randolph) would accelerate R&D and provide grants for mitigation at damaged sites. S.1211 (Hollings) would facilitate the use of natural gas in large boilers.

2. Bills that would allow or encourage the use of simultaneous SO_2/NO_x controls include H.R. 132, H.R. 3251, S. 769, S. 2001, H. R. 4906, and H.R. 5370.

3. "Emission Costs and Engineering Assessment," report prepared by Work Group 3B under the U.S./Canada Memorandum of Intent on Transboundary Air Pollution, June 1982 (as reported in "Tax Strategies to Fund Acid Rain Control," a staff memorandum prepared by OTA Oceans and Environment Program, August 1983, Table 1).

4. "Analysis of the Waxman-Sikorsky Sulfur Dioxide Emission Reduction Bill (H.R. 3400)," prepared for EPA by ICF Inc., April 1984, p. 2-3.

5. "Estimates of Sulfur Oxide Emissions from the Electric Utility Industry, Volume I," EPA-600/7-82-061a (NTIS PB 83-130229), July 1982.

6. "Additional Analyses of H.R. 3400, The National Acid Deposition Control Act of 1983," a staff memorandum prepared by the OTA Oceans and Environment Program, September 18, 1983, Table 4.

7. "Acid Rain and Transported Air Pollutants: Implications for Public Policy," U.S. Congress, Office of Technology Assessment, OTA-O-207, Washington, D.C., June 1984, p. 168 ff.

8. Ibid, p. 157.

9. Ibid, p. 168.

10. Ibid, pp. 180-181. By linear scaling of figures in Table A-15 (2.5 mills/kWh to produce revenue of $5 billion/yr).

11. Ibid, p. 169.

12. Ibid, p. 179.

13. "Full-Scale Desulfurization of Stack Gas by Dry Limestone Injection," F. E. Gartrell, TVA, August 1973, EPA-650/2-73-019-a,b,c (NTIS PB 228447, 230384, 230385).

14. Zallen, D., et al., "The Generalization of Low Emission Coal Burner Technology," in Proceedings of the Third Stationary Source Combustion Symposium, Volume II, EPA-600/7-79-050b (NTIS PB 292540), February 1979.

15. "EPA's LIMB R&D Program--Evolution, Status, and Plans," G. Blair Martin and James H. Abbott, EPA/AEERL. Presented at the First Joint Symposium on Dry SO_2 and Simultaneous SO_2/NO_x Control Technologies, Nov. 13-16, 1984, San Diego, California.

16. "Distributing Acid Rain Mitigation Costs: Analysis of a Three-Mill User Fee on Fossil Fuel Electricity Generation," L.B. Parker, Congressional Research Service, April 11, 1983.

17. "Analysis of a Senate Emission Reduction Bill Assuming the Availability of LIMB Technology," by ICF, Inc., for EPA. April 1983.

18. "Analysis of a Senate Emission Reduction Bill (S.3041) Assuming the Availability of the LIMB Technology," an unpublished report prepared for EPA's Office of Policy Analysis by ICF, Inc., April 1983, pp. S-8 and S-9.